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Physical properties of thin particleboard made from saline eucalyptus

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Abstract

Eucalyptus tree, *Eucalyptus cinerea*, has the potential to be used as a biomass crop to help manage saline subsurface drainage water in arid land where irrigated agriculture is practiced. In this research, saline eucalyptus was used to manufacture medium-density particleboard in an attempt to develop value-added application for the saline wood. This study investigated the effects of wood species (non-saline and saline), particle size, adhesive, bark content (BC), resin content (RC), and hot water treatment on the mechanical and water resistant properties of the medium-density particleboards made with eucalyptus woods. The measured mechanical properties included tensile strength (TS), modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB) of the finished particleboards. Water absorption and thickness swelling were tested to evaluate the water resistance properties. The particleboard made with 4% polymeric methane diphenyl diisocyanate (PMDI) resin had better qualities except for MOR than the particleboard made with 7% urea formaldehyde (UF). The particles of medium size (20–40 mesh) gave higher particleboard qualities, except for TS, than the smaller size (40–60 mesh) and larger size (10–20 mesh) particles. The qualities of particleboard were improved as the content of UF resin increased from 7% to 16%. The mechanical properties deteriorated as BC increased from 0% to 15.4%, but the water resistance was improved. The particleboard made from hot water treated wood particles had better qualities than the particleboard made from untreated particles. The particleboard made from saline wood had much better qualities than the particleboard made from non-saline wood. Saline eucalyptus is an appropriate material for manufacturing particleboards.

Keywords: Saline wood; Eucalyptus; Particleboard; Urea formaldehyde; Polymeric methane diphenyl diisocyanate; Mechanical properties; Water resistance

1. Introduction

Reuse of drainage water for irrigation is one of several options that farmers in California's San Joaquin Valley (SJV) are pursuing for managing subsurface drainage to alleviate problems with soil salinity and perched water tables. Environmental regulations restrict the discharge of agricultural drainage water into local water body. An innovative farm management system called integrated on-farm drainage management (IFDM) has been tested on a farm in the SJV. The IFDM uses drainage water to irrigate some salt tolerant crops, including Eucalyptus, Athel, Jose Tall Wheatgrass, and Creeping Wild Rye. The saline crops capture solar energy through photosynthesis and play an important role in transpiration of water

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and concentration of salts. However, in order to assure the sustainability of growing the saline crops, effective utilization of biomass from the crops is important. In this study, the feasibility of using saline eucalyptus as a suitable raw material for manufacturing particleboard was investigated.

Particleboard has been widely used throughout the world for furniture manufacture and house construction, including flooring systems, stair treads, and underlayment, etc. (Youngquist, 1999; Sellers, 2000). Recently, the demand for particleboard has continued to increase for housing construction and furniture manufacturing (Sellers, 2000). In 1998, 56.2 Mm^3 of particleboard was consumed worldwide (Youngquist and Hamilton, 2000). In 1999, approximately 85% of interior type particleboard was used as core stock for various furniture and cabinet application. Particleboard products are also commonly used for home decking and floor underlayment (Youngquist, 1999). The 76 particleboard mills in North America produced about 11 Mm^3 particleboards, accounting for 19% of the total wood composites manufactured in North America (Sellers, 2000, 2001).

Much research has been done on the use of various woods for particleboard manufacture. A summary of the selected studies is provided in this paper. Hiziroglu et al. (2002) investigated the use of Eastern Redcedar (*Juniperus virginiana* L.) to manufacture a commercial single-layer particleboard and reported that the Eastern Redcedar could be a suitable raw material to manufacture particleboards for commercial use. Oh et al. (2003) evaluated the strength properties and water resistance of wood composites from four Korean thinning logs, including *Pinus rigida* Miller, *Pinus densiflora* Sieb. et Zucc, *Larix leptolepis* Gordon and *Quercus acutissims* Carruthers. They reported that even though particleboards had significantly different physical strength and water resistance properties due to the different wood species, all of the thinning logs were suitable raw materials for particleboard manufacture. Nemli et al. (2004) manufactured medium-density particleboard from black locust (*Robibia pseudoacacia* L.) and noted that the tannin contents of black locust had significant effects on the properties of particleboards. Silica, phenol, and some oxidants, including CuO, CrO_3 and As_2O_5, have been reported to have significant effects on improving the mechanical properties, water resistance, and decay resistance of particleboards (Huang and Cooper, 2000; Clausen et al., 2001; Zhou and Kamden, 2002; Nemli et al., 2004).

The literature on using saline biomass for particleboard manufacture is scarce. In a recently study at the University of California at Davis, Zheng et al. (2006) found that the particleboard made from saline Athel, *Tamarix aphylla* L. possessed high mechanical properties and water resistance, which may have been due to the presence of some salts. Therefore, saline eucalyptus may also be used as raw material for manufacturing particleboard, which is the focus of this study.

The objectives of this study were to (1) compare the qualities of saline and non-saline eucalyptus particleboards, (2) characterize the mechanical properties and water resistance of medium-density particleboards made from saline eucalyptus as affected by wood particle size, adhesive type, bark content (BC), resin content (RC), and hot water treatment, and (3) study the effect of moisture content (MC) and BC on the pH values of wood particles.

2. Materials and methods

2.1. Materials

Polymeric methane diphenyl diisocyanate (PMDI) (100% solid content) and urea formaldehyde (UF) (C-TH39, 65.6% solid content) were used as the adhesives for making the particleboards. The UF and PMDI were obtained from Borden Chemical Company (Hope, AR) and Bayer Polymers LLC (Pittsburgh, PA), respectively. Ammonium sulfate was purchased from Fisher Scientific Chemical Co. (Fair Lawn, NJ) and used as curing catalyst for the UF resin.

Saline eucalyptus from 8-year-old trees was collected from the farm located near Five Points, California and then cut into approximately 40 cm long logs. The logs used in this study were from 16 trees with diameters ranging from 3 to 22 cm with harvest MC of 16.6–23.6%, which was measured according to the ASTM standard method (D4442-92, ASTM, 1997a). The average density and bark fraction of the logs were 0.77 g/cm^3 and 17.1%, respectively. All reported MC values are on oven-dry basis (db) unless specified otherwise. The logs were further reduced into 5–10 cm long chips with a Dosko Brush Chipper (Model 1400-12) before the chips were air-dried to about 7.5% MC at the Biomass Laboratory at the University of California at Davis. A 0.5 m long non-saline eucalyptus log (*Eucalyptus camaldulensis*) from an 8-year-old tree planted with fresh water was obtained from another farm near Davis, California. The average diameter, density, and bark fraction of the non-saline eucalyptus were 10 cm, 0.76 g/cm^3 and 17.4%, respectively. The chips were prepared using the same procedure for the saline eucalyptus.

2.2. Experimental design

2.2.1. Effects of particle size, wood type, bark content, adhesive content and hot water treatment

High quality particleboards of high strength, smooth surface, and equal swelling are normally obtained by using a homogeneous material with a high degree of slenderness (long and thin particles), but without oversized particles, splinters, and dust. To determine the appropriate particle size for producing such high quality particleboard, the eucalyptus chips were separated by hand into heartwood and bark portions using a chisel. The heartwood portion was then milled with a hammer mill (Model C269OYB, Franklin Co. Inc., Buffton, IN). The resulting particles of three different sizes, 10–20, 20–40, and 40–60 mesh, were used to make particleboards using 7% UF resin to determine the effect of particle size on the qualities of particleboards. According to the recommendation of Youngquist (1999), 7% UF was used for all particleboard manufacture in this study, unless specified. Because the test results showed that the particleboard made with 20–40 mesh particles had the highest overall qualities, 20–40 mesh particles were used for making the rest of particleboards. In order to determine the appropriate mill screen size for obtaining the high yield of 20–40 mesh particles, the heartwood chips were milled with three different screens that had 1.27, 0.64, and 0.32 cm openings. The particle size distributions were analyzed using a modified ASTM standard method (E828-81, ASTM, 1997b) with a sieve shaker (ROTAP, The W.S. Tyler Company, Cleveland, OH) and sieves (Newark Wire Cloth Co.). Because the 0.32 cm opening screen produced the highest yield of 20–40 mesh particles, it was used for preparing particles for all the experiments. The wood particles were then stored in a chamber to maintain a constant MC of 7.5% in an environment of 52% relatively humidity (RH) and $21 \pm 1\,^{\circ}$C temperature until they were used.

To investigate the difference in quality of saline and non-saline eucalyptus particleboards, the qualities of the two types of particleboards were evaluated and compared. The non-saline particleboards were also manufactured with 7% UF and without bark content.

To study the effects of RC of UF and BC on the qualities of particleboards, a 4×3 full factorial design was employed (Neter et al., 1996). The bark was separated from heartwood using a chisel and prepared into the particles using the same procedure as for heartwood particles. The tested levels of RC were 7%, 10%, 13%, and 16% based on the total weight of wood particles, and the levels of BC were 0%, 8%, and 15.4%, which were prepared by using debarked heartwood particles, mixing debarked particles and bark particles, and using particles from chips without debarking, respectively. The bark particles used here had the same size and MC as the heartwood particles. The qualities of the particleboards were fully evaluated with the methods specified in the following section.

Because PMDI has been used for making particleboard by industry and normally performs better than UF, it was also used as adhesive in this study. The quality of particleboards with 4% PMDI (Youngquist, 1999) and 7% UF resins were compared.

The qualities of particleboards made from saline particles with and without hot water treatment were compared to determine the effectiveness of hot water treatment. Yasin and Qureshi (1990) improved eucalyptus particleboard properties by treating the wood particles with hot water. Their method was modified and used in this study. The 20–40 mesh particles without bark were soaked in water contained in a beaker and heated in a water bath at $100\,^{\circ}$C for 1 h. The suspension was then filtered using a Büchner funnel and washed using hot distilled water for three times to remove the soluble extractives. The wet particles were dried in an oven at $60\,^{\circ}$C for about 2 days until the moisture content of particles reached 7.5% and then the particles were used to make particleboards with 7% UF resin.

2.2.2. Effect of MC on pH values of particles

Because the MC of the particles is directly related to pH value, which affects the performance of adhesive and qualities of particleboards, the relationships between the MC and pH were studied for the particles with the three different BC levels (0%, 8%, and 15.4%). The 40–60 mesh particles were oven-dried to obtain four different MC levels (2.0%, 4.2%, 6.4%, and 7.5%). The pH of wood particles was determined according to the method described by Lebow and Winandy (1999) with a pH meter (AR20, Fisher Scientific Inc.). One-gram particle sample at each MC was soaked in 20 ml distilled water. The solution was kept at $20 \pm 1\,^{\circ}$C, shaken for 30 min, and then left still for 10 min in a water bath (Model R76, Reciprocal Cal Water Bath Shaker, New Brunswick Sci. Co., Inc., NJ) before pH was measured. The relationship between MC and pH values of the wood particles was analyzed.

2.3. Particleboard manufacture

The particleboards were manufactured using the procedures outlined by Youngquist (1999). Adhesive resin, UF or PMDI, at the specified levels in the experiment design section, was mixed with wood particles for 8 min at room temperature (20–22 °C) using a mixer (Model KP267XBK; KitchenAid, Greenville, OH). When UF was used, 1% (w/w) ammonium sulfate was added as a curing catalyst, based on the solid content of the UF. The glued particles were then pre-pressed into a 2 cm thick single layer mat in a 22.8 cm × 22.8 cm wood mold with four removable cubic steel stops (0.55 cm × 0.55 cm × 0.55 cm).

Because the density was an important factor affecting the particleboard qualities, the bulk densities of all experimental particleboards were controlled at a constant level of about 0.72 g/cm^3, which corresponded to 0.55 cm thickness of the finished particleboard. Similar stops from the wood mold were used in the hot press to allow the same thickness of particleboards to be achieved for all the test runs. To control the density, the theory proposed by Yossifov (1988) was modified and used to calculate the relative amount of resin and wood particles. For PMDI, the press time, temperature and pressure were 8 min, 140 °C and 3 MPa, respectively. For UF, the pre-pressed mat was pressed for 5 min in a hot-press (Model 3891 Auto “M”, Carver, Inc., Wabash, IN) with the temperature and pressure controlled at 152 °C and 3 MPa, respectively. The finished particleboards were trimmed to avoid edge effects and then cut into various sizes for property evaluation.

2.4. Particleboard property evaluation

Water resistance, including thickness swelling and water absorption, and mechanical properties, including modulus of rupture (MOR), modulus of elasticity (MOE), tensile strength (TS), and internal bond strength (IB) are very important parameters for particleboards. They were measured for each finished particleboard. Data analysis was performed using an SAS software package (SAS Institute, Raleigh, NC, 1992). The significance of different treatments was determined using analysis of variance (ANOVA) and least significant difference (LSD) ($\alpha = 0.05$). All reported values are the average of three replicates.

2.4.1. Mechanical properties

Finished particleboards were cut into various specimens according to ASTM standard method (D1037-99, ASTM, 1999). The rectangular pieces of 3.8 cm × 15.2 cm and 5.1 cm × 17.8 cm were used for TS determination and three-point-flex measurement of MOR and MOE, respectively. The square pieces of 5.1 cm × 5.1 cm were used for IB measurement. The mechanical properties were determined using an Instron testing machine (Model 1122; Instron Corporation, Canton, MA) with the speed of movable crosshead being 4 mm/min for TS test and 5 mm/min for three-point-flex and IB tests. Each reported value is the average of three measurements.

2.4.2. Water absorption and thickness swelling

Water absorption and thickness swelling of particleboards were determined according to the ASTM standard method (D1037-99, ASTM, 1999). The square samples of 15.4 cm × 15.4 cm were soaked in water at room temperature (20–22 °C) for 2 h and 24 h to determine short- and long-term water resistance properties, respectively. The weight and thickness of the sample were measured before and immediately after soaking and used to calculate water absorption and thickness swelling and reported as percentages of the values before soaking.

2.4.3. EMC measurement of finished particleboard

The equilibrium moisture contents (EMC) of saline and non-saline eucalyptus particleboards with 7% UF using particles without bark at three different RH levels were determined using the method of Rowell et al. (1995). The particleboard specimens were stored in the chambers (Fisherbrand® Desiccator Cabinet) with constant RH levels of 50%, 65%, or 85% and temperature 21 ± 1 °C for about 7 days. The weight changes of all specimens were measured every 24 h until no change was observed. The EMC (dry basis) was calculated as

$$\mathrm{EMC} = \frac{\mathrm{CPW} - \mathrm{DWP}}{\mathrm{DWP}} \times 100\% \qquad (1)$$

where CPW is conditioned particleboard weight and DWP is the dry weight of particleboard.

2.5. Contact angle measurements

To determine the compatibility between the adhesives and saline eucalyptus particles, the contact angles between adhesives and eucalyptus were measured using a contact angle goniometer (Model 100, Ramé-hart Instrument Co.) under standard conditions (50% relative humidity and 23 °C). The method described by Boquillon et al. (2004) was modified and applied in this study. The 5 μl adhesives were dropped onto 1 cm × 1 cm × 0.1 cm eucalyptus flakes using a 5 μl syringe. The contact angle between wood surface and the adhesive, UF or PMDI, was observed over a 2 min period every 5 s.

Table 1
Mechanical and water resistance properties of particleboards made of different particle sizes

Particle size (mesh)	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swelling (%)	
					2 h	24 h	2 h	24 h
10–20	11.1 c	1406.1 b	6.1 c	1.20 b	72.39 b	86.22 b	37.00 a	43.91 a
20–40	13.6 a	1564.2 a	7.1 b	1.31 a	69.89 c	81.86 c	31.26 c	38.28 b
40–60	12.7 b	1352.5 c	8.5 a	1.05 c	85.03 a	98.36 a	36.05 b	39.12 b

Note: Values within the same column followed by different letters (a–c) are significantly different at $P<0.05$. The particleboards were made with 7% UF and particles without bark.

3. Results and discussion

3.1. Effect of particle size on particleboard properties

Among three particle sizes tested (10–20, 20–40, and 40–60 mesh), the 20–40 mesh resulted in the highest MOE, MOR, and IB values (Table 1) except for TS. The particles of this size were covered better by the resin and had tighter bonds. The surface area of the 40–60 mesh particles, might be too large to be covered adequately by the adhesives when the same mass ratio of adhesives and particles was used (Wang and Sun, 2002). The 10–20 mesh particles may be too large and resulted in weak contact between the particles so that the pores between particles could be easily seen and not all the particles were bonded well by the resin.

The particleboards with different particle sizes showed significant differences in water absorption and thickness swelling. The particleboard made from 20 to 40 mesh particles had the lowest water absorption and thickness swelling, which was consistent with the mechanical property results.

Because the particleboards with 20–40 mesh particles had the most desirable quality, the production of high 20–40 mesh particles is recommended for the milling of the chips. The size distributions of the particles obtained from the hammer mill with three different screen sizes are listed in Table 2. The screen with 0.32 cm openings yielded the highest percentage of 20–40 mesh particles, and therefore, it was used for preparing wood particles for all other experiments.

Table 2
Weight percentage (%) of wood particles in different sizes

Particle sizes (mesh)	Screen sizes of hammer mill (cm)		
	1.27	0.64	0.32
>6	15.7	0.1	0.2
6–10	34.2	0.4	1.5
10–20	35.3	6.6	22.9
20–40	11.7	36.1	47.9
40–100	2.5	44.8	23.8
100 to Pan	0.4	9.2	3.4
Total	99.8	97.2	99.7

3.2. Comparison between saline and non-saline eucalyptus particleboard

Saline eucalyptus particleboard had significantly higher qualities than non-saline particleboard except for the IB (Table 3), when 7% UF and particles without bark were used to manufacture the particleboards. The MOE of saline eucalyptus particleboard was about twice as much as the MOE of non-saline particleboard. Especially with respect to water resistance, saline particleboards had absolute advantages over non-saline particleboards. After 24 h soaking, the water absorption and thickness swelling of saline particleboard were only 1/2 and 1/6 of those of non-saline particleboard, respectively.

The EMC is an important quality parameter for determining the applications of particleboards. High EMC could limit the use of particleboards due to weakened stability at high RH levels. The EMC of non-saline particleboard was similar to that of saline particleboard

Table 3
Comparison of saline and non-saline eucalyptus particleboard properties

Sample	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swelling (%)	
					2 h	24 h	2 h	24 h
Saline	13.6 a	1564.2 a	7.1 a	1.31 b	69.89 b	81.86 b	31.26 b	38.28 b
Non-saline	8.0 b	745.0 b	5.6 b	1.57 a	100.00 a	148.01 a	129.50 a	209.03 a

Note: The particleboards were made with 7% UF and particles without bark.

Table 4
Effect of RH on EMC of the particleboard

Selected aqueous salt solution	RH (%)	EMC (%)	
		Saline	Non-saline
$Mg(NO_3)_2 \cdot 6H_2O$	50	3.90 c	3.92 c
$CoCl_2$	65	4.10 b	4.09 b
KCl	85	4.46 a	4.50 a

Note: Values within the same column followed by different letters (a–c) are significantly different at $P < 0.05$. The particleboards were made with 7% UF and particles without bark.

at three RH levels (Table 4). The EMC of both saline and non-saline particleboards increased by about 15% as RH increased from 50% to 85%. This indicates that the non-saline and saline eucalyptus particleboards could perform equally well in the environments of relatively high humidity without considering the mechanical properties and water resistance.

Based on the analysis results from Hazen Research, Inc. (Golden, CO), the ash components of the saline and non-saline eucalyptus wood were significantly different (Table 5). The normalized amount of Fe_2O_3 content of non-saline eucalyptus was approximate 60 times more than that of saline (wt%, wet basis). The differences in chemical compositions could be one factor causing the differences in particleboard qualities. The structures and cell components of different species might also bring about such differences in particleboard qualities. The colors of non-saline and saline particleboard were different, red-brown versus light-brown, which might be due to the different compositions. The explanation as to why the saline eucalyptus particleboard was much better than non-saline eucalyptus particleboard is worthy of pursuit for further application of saline eucalyptus.

Table 5
Ash compositions of both non-saline and saline eucalyptus

Chemical compositions	Non-saline (wt%)	Saline (wt%)
SiO_2	2.77	2.92
Al_2O_3	3.14	1.00
TiO_2	0.22	0.02
Fe_2O_3	20.21	0.26
CaO	14.70	38.40
MgO	12.00	5.83
Na_2O	3.38	5.02
K_2O	18.40	10.10
P_2O5	13.59	3.23
SO_3	1.25	2.16
Cl	1.90	3.31
CO_2	10.73	29.36

Note: Non-saline eucalyptus has 1.30% ash content (wt%, wet basis) and the saline eucalyptus has 1.75% ash content (wt%, wet basis). Analysis made by Hazen Research, Inc. (Golden, CO).

3.3. Effect of BC and RC on particleboard properties

In general, BC and RC had significant effects on the mechanical properties of particleboard, even though little interaction was observed between them based on the ANOVA analysis results (Table 6). At a constant level of BC, higher RC resulted in higher mechanical properties, which was expected. However, higher RC also means higher production cost. Proper levels of RC should be determined by meeting quality requirements for a specific application with considerations of reasonable cost.

The particleboard with bark had lower mechanical properties than the particleboard without bark. For example, the MOR values of the particleboards made from heartwood were 9.5–15.3% higher than the particleboard

Table 6
Mechanical and water resistance properties of particleboards with different UF resin contents (RC) and bark contents (BC)

BC (%)	UF RC (%)	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swelling (%)	
						2 h	24 h	2 h	24 h
0	7	13.6 c	1564.2 g	7.1 f	1.31 cde	69.89 a	81.86 a	31.26 a	38.28 a
0	10	24.1 ab	2240.2 e	13.1 c	1.46 bc	55.89 d	73.19 b	21.90 d	24.95 c
0	13	25.3 ab	2474.8 c	13.4 bc	1.49 b	37.61 g	62.22 f	15.93 f	20.71 de
0	16	27.7 a	2831.1 a	15.2 a	1.57 a	32.18 hi	54.55 h	12.69 gh	18.37 ef
8	7	13.5 c	1395.1 h	6.8 fg	1.25 de	62.14 b	78.22 c	27.82 b	30.11 b
8	10	22.7 ab	2215.7 e	11.3 e	1.34 bcde	45.51 e	67.02 d	19.30 e	22.61 cd
8	13	24.5 ab	2358.8 d	12.6 cd	1.41 bcd	33.65 h	58.76 g	13.91 g	18.64 ef
8	16	26.7 ab	2628.7 b	14.3 ab	1.48 b	30.56 i	53.13 h	11.52 h	16.24 gf
15.4	7	12.2 c	1243.0 I	5.7 g	1.18 e	59.10 c	70.09 e	23.77 c	28.18 b
15.4	10	20.9 b	2127.7 f	11.0 e	1.28 de	40.35 f	63.74 f	18.79 e	21.97 d
15.4	13	23.1 ab	2237.9 e	11.6 de	1.35 bcd	32.62 h	52.96 h	12.12 h	16.95 gf
15.4	16	24.9 ab	2458.2 c	12.9 c	1.40 bcd	28.12 j	48.61 i	9.41 i	15.15 g

Note: Values within the same column followed by different letters (a–j) are significantly different at $P < 0.05$.

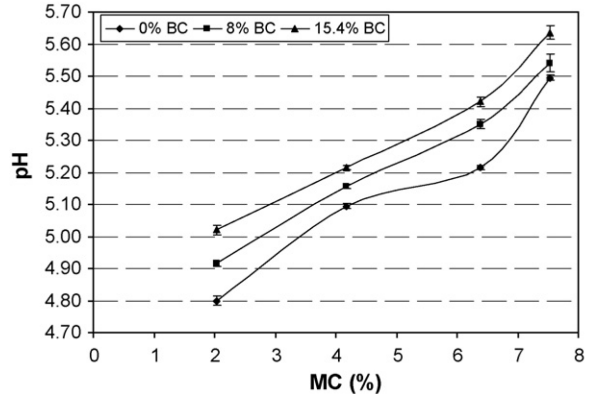

Fig. 1. Effect of moisture content (MC) and bark content (BC) on the pH of eucalyptus wood particles.

made from the particles of whole wood. This could be due to the fact that the presence of bark caused higher pH and/or lower absolute acid buffering capacity of wood particles, which could have extended the gel time of UF resin and inhibited the curing of UF (William and Niazi, 1980; Sauter, 1996; Mo et al., 2003; Zhang et al., 2003), causing the deterioration of bonding quality between fibers and UF (Moslemi, 1935; Semple et al., 2002). In addition, the weaker mechanical strength of bark could also contribute to the lower mechanical properties of particleboard with bark. At a constant MC, the presence of bark in the particles caused slight increase in pH, which could be due to less acidic chemicals contained in bark than in heartwood (Fig. 1). The results indicated that the bond between UF and heartwood particles could be stronger than the bond between UF and bark particles, because the lower pH is more favorable to improving the bond quality of UF, which is a pH sensitive resin (Sauter, 1996). The pH of wood particles was significantly affected by MC of particles. The pH increased from 4.81 to 5.49, from 4.91 to 5.56 and from 5.01 to 5.62 for 0%, 8% and 15.4% BC, respectively, as MC increased from 2.0% to 7.5% (Fig. 1). The results of the relationship between pH and MC of wood particles were similar to that of Goto and Onishi (1967). The relationship between MC and pH should be an important factor needed to be considered when manufacturing particleboard using UF resin.

Except for the particleboards with 7% RC, the mechanical properties of all the particleboards exceeded the minimum mechanical property requirements for type M-2 particleboard for industrial use according to US Standard ANSI/A208.1 (CPA, 1999). Therefore, the debarking process may not be necessary when eucalyptus wood is used for making M-2 particleboard with 10% or more UF resin. It was noticed that the IB values of the particleboards were significantly higher than the values specified in the standard. The particleboard made from particles without bark and 16% UF had the best mechanical properties in the tested range. Its mechanical properties even exceeded the minimum mechanical property requirements for type M-3 particleboard for industrial use.

The results for the 2 and 24 h water absorption and thickness swelling are also presented in Table 6. In general, water absorption and thickness swelling significantly decreased with the increase of UF content. The presence of bark in the particleboards resulted in higher water resistance and inconsistent with results related to the mechanical properties. It has been reported that some polyphenolic extractives in bark could react with UF to improve the water resistance properties, although bark could cause weaker mechanical properties to some extent (Nemli et al., 2004; Hofstrand et al., 1984). In addition, eucalyptus bark could contain higher hydrophobic substances, such as oil and silica, than heartwood so that higher BC could give higher water resistance properties. ANOVA results indicate that there was little interaction between RC and BC on the water resistance of particleboards.

It has been suggested that furniture particleboards require less than 60% long-term water absorption and less than 25% long-term thickness swelling (Yossifov, 1975; Maloney, 1977). Based on such suggested requirements, the particleboards with 10% or more RC can be used for furniture manufacture without further treatments. To improve the water resistance and reduce thickness swelling, three different methods may be used based on current practices in the particleboard manufacturing industry. The first method is to add wax (0.5–1%) to the mixture of adhesive and particles during the manufacturing process. The second method is to decrease "springback" effect by reducing the density of the particleboards (Okino et al., 2004). If reducing particleboard density is not desirable for certain applications, adding wax should be considered even though the mechanical properties may be lowered (Grigoriou, 2003; Okino et al., 2004; Papadopoulos et al., 2002, 2004). The third method is to use acetylation of particles (Wisherd and Wilson, 1979; Hofstrand et al., 1984). Based on the obtained results in this study, adding more bark might be another alternative to improve the water resistance of particleboard; however, the lowered mechanical properties need to be carefully considered.

The particleboards with 15.4% bark content and 10–13% UF resin have met the requirements of mechanical properties of US Standard ANSI/A208.1. They also met the recommended values of water resistance for furniture manufacture. Therefore, debarking may not be necessary when the particleboards are used for furniture.

3.4. Effect of UF and PMDI adhesives on particleboard properties

Compared with 7% UF particleboard, the 4% PMDI particleboard had significantly higher MOE, and IB, but significantly lower MOR. The two particleboards did not have significant difference in TS (Table 7). The contact angles between eucalyptus and adhesives (PMDI and UF) were measured as 24° and 65°, respectively. The results indicated that PMDI had better compatibility with the eucalyptus than UF. However, particleboard with 4% PMDI did not show significant advantage over the particleboard with 7% UF as expected. Because the strength of PMDI particleboard partially results from the reaction between PMDI and water in the particles, 7.5% MC of particles may not be enough for complete polymerization of PMDI during the hot press process.

The test results of water absorption after 2 and 24 h soaking showed that the PMDI particleboards had better qualities than the UF particleboard (Table 7). The long-term water absorption of PMDI particleboard was about 15% lower than that of UF particleboard and maintained relatively stable dimensions. The PMDI particleboard had about 50% less long-term thickness swelling than the UF particleboard. The thickness swelling could be affected by bond quality (Sauter, 1996) and adhesive properties (Boquillon et al., 2004). Because the particle bonds resulted from UF was not as strong as the bonds from PMDI, more water was able to penetrate into the particleboard, resulting in significant swelling. It is well known that PMDI has a significantly higher water resistance than UF because of the chemical properties of PMDI and UF, which are 100% diisocyanate solid and water based adhesives, respectively (Vick, 1999). One of the characteristics of eucalyptus is the oil content (Steinbauer and Matsukit, 2004). The oil may have acted as wax that is normally added for typical particleboard manufacture for improving water resistance properties. Another possibility was that the oil can easily react with PMDI to improve the bonding quality between PMDI and eucalyptus. Therefore, the PMDI particleboards had better water resistance properties than UF particleboards. For thickness swelling, PMDI particleboards were higher than the 8% required for home decking particleboard by the US Standard ANSI/A208.1. The thickness swelling may be reduced by adding wax or other hydrophobic substances during particleboard manufacture (Nemli et al., 2004), which needs to be further studied.

3.5. Effect of hot water treatment on particleboard properties

When the wood particles were treated with hot water, the color of water after treatment was dark red. The color of treated wood particles was much lighter than the color of the untreated particles. The particleboard made from treated particles had higher mechanical properties than the particleboard made from untreated particles

Table 7
Mechanical and water resistance properties of particleboards bond with 7% UF and 4% PMDI

Adhesive	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swelling (%)	
					2 h	24 h	2 h	24 h
PMDI	10.4 b	1651.9 a	7.1 a	1.45 a	16.99 b	48.22 b	12.50 b	26.95 b
UF	13.6 a	1564.2 b	7.1 a	1.31 b	69.89 a	81.86 a	31.26 a	38.28 a

Note: Values within the same column followed by different letters (a and b) are significantly different at $P < 0.05$. The particleboards were made with particles without bark.

Table 8
Mechanical and water resistance properties of particleboards made from hot water treated particles

Sample	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swelling (%)	
					2 h	24 h	2 h	24 h
Treated	18.5 a	1839.2 a	10.2 a	1.59 a	53.46 b	74.06 b	20.47 b	25.13 b
Untreated	13.6 b	1564.2 b	7.1 b	1.31 b	69.89 a	81.86 a	31.26 a	38.28 a

Note: Values within the same column followed by different letters (a and b) are significantly different at $P < 0.05$. The particleboards were made with 7% UF and particles without bark.

(Table 8). Such results would imply that some alkaline oxidant extractives such as CaO, K_2O, and Na_2O in the wood particles could cause a negative effect on the curing of UF during the hot press process. The hot water treatment may have removed these alkaline oxidant extractives, decreased the pH, and increased the absolute acid buffering capacity of wood particles. Thus, the interaction between the UF and wood particles was improved and particleboards made from treated particles bonded by UF had better qualities than the untreated particles (Xing et al., 2004). The changes in the chemical composition and properties of wood particles as caused by hot water treatment and their possible effect on the mechanical properties of particleboard still need to be investigated. The changes in structure (e.g., cell wall components) and/or the surface properties of particles caused by the hot water treatment might also contribute to the higher mechanical properties of the particleboards.

Improvement in the water resistance with hot-water treatment should expand its use. The particleboards made with treated particles had significantly lower short-term and long-term water absorption and thickness swelling than untreated particleboards (Table 8). Their long-term water absorption and thickness swelling decreased by about 10% and 34%, respectively, than the untreated particleboards. Therefore, hot water treatment is recommended for making such particleboards.

4. Conclusion

Saline eucalyptus is a suitable raw material for making particleboards. High quality saline eucalyptus particleboards were obtained by using wood particles of 20–40 mesh. Saline eucalyptus particleboards had superior physical qualities than the non-saline with the exception of IB. However, their EMC did not show significant difference under three RH levels (50%, 65%, and 85%). Generally, the particleboards made with 4% PMDI had better quality than the particleboards made with 7% UF, especially the water resistance. When water resistance is important, PMDI appears to be the preferred adhesive for particleboard fabrication even though its cost could be higher than UF. The quality of particleboards was improved with the increase of UF content in the tested range from 7% to 16%. The presence of bark in the particles resulted in slightly increased pH of particles and reduced the mechanical properties, but improved the water resistance of finished particleboards. Particleboards manufactured from hot water treated particles had higher qualities than the particleboard made from the untreated particles.

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